Short Baseline Neutrino Program Overview

Speaker: Corey Adams

Introduction

This talk is a long (sorry!!) presentation about the Short Baseline program at Fermilab.

This talk is **"From MicroBooNE to MicroBooNE,"** which means that almost all of the results you see are produced by MicroBooNE collaborators.

A comment ...

Please feel free to interrupt this talk with physics comments, questions, or anything else relevant to the analysis.

While this is a talk working towards approval of these plots, please send aesthetic comments by email - many plots here are not in final form and are illustrative and this talk is long enough as it is!

The intention is to show the analysis methods and the current draft plots so that when they are ready and are inserted into the SBN report, there are no surprises.

Documentation

There are many references for this entire endeavor.

While it seems like cheating, I haven't listed them here and instead will direct you to the far more organized reference sections in:

- The SBN Conceptual Report (released soon)
- The LAr1-ND CDR (released soon)
- The technote on docdb 3732
- The original LAr1-ND Proposal
- The SBN Status Report from July 2014
- The "lar1" branch of LArLight

Event Rate Calculations

Oscillation Analysis

ν_e Appearance is driven by the search for an excess signal on top of a predicted background.

- Reduce background
- Quantify errors on background

ν_μ Disappearance is looking for an absence of events from a predicted spectrum.

- Constrain expected rate to as high precision as possible

The different drivers mean the two searches approach their event selection in different ways.

Event Selection

Select events by topology: Looking for a single shower event that does not have an obvious gap between the shower and a vertex with charged activity.

Select events by looking for events with a contained track consistent with a muon, or one that is exiting but has enough contained to reconstruct energy.

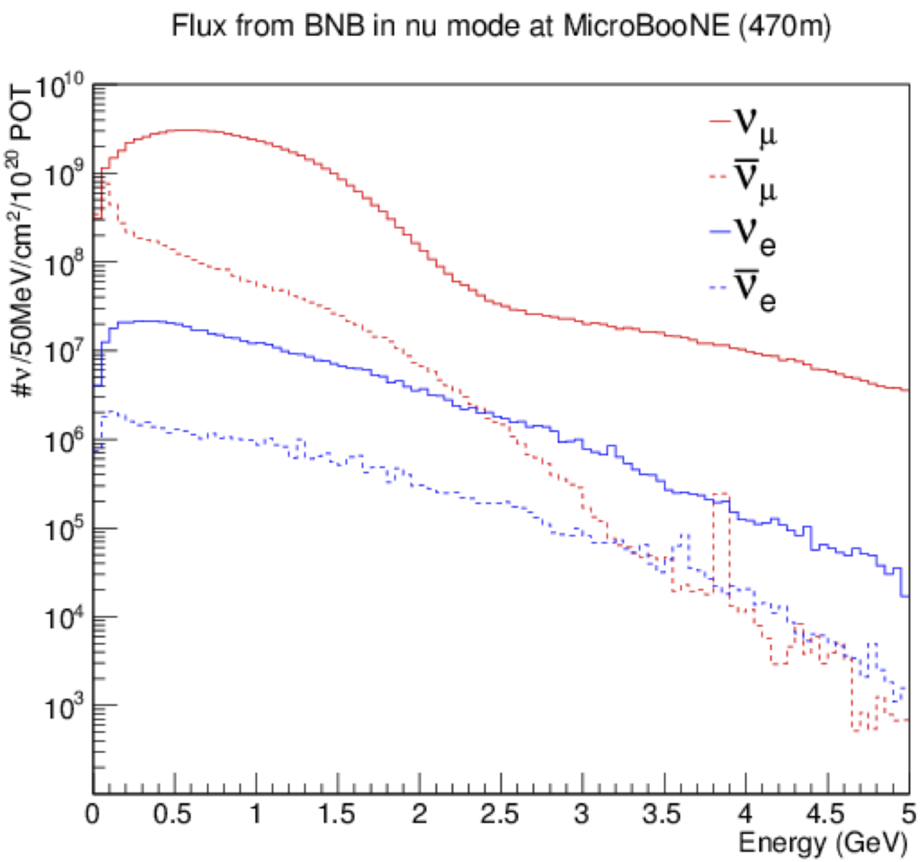
ν_e Background Event Candidates

ν_e events can come from:

- Intrinsic beam electron neutrinos (irreducible background).
- Neutrino Electron Scattering (Irreducible but small background)
- Neutral Current Single Photon Misidentification
- ν_μ Charged Current Misidentification
- Dirt Neutrino Interactions
- Cosmics

Not covered in this talk.

ν_e Intrinsics



Electron neutrino contamination in the Booster beam is ~0.5%.

The neutrinos come from:

kaon decay $K \to \nu\, \mu$

muon decay $\mu \to \nu \nu e$

ν - electron Scattering

Two options:

$$\nu_\mu + e^+ \rightarrow \nu_\mu + e^+ \quad \text{(NC only)}$$
$$\nu_e + e^+ \rightarrow \nu_e + e^+ \quad \text{(CC or NC)}$$

Detector Signature: **Forward going electron with no vertex activity**

Irreducible background but ~negligible compared to others due to low cross section.

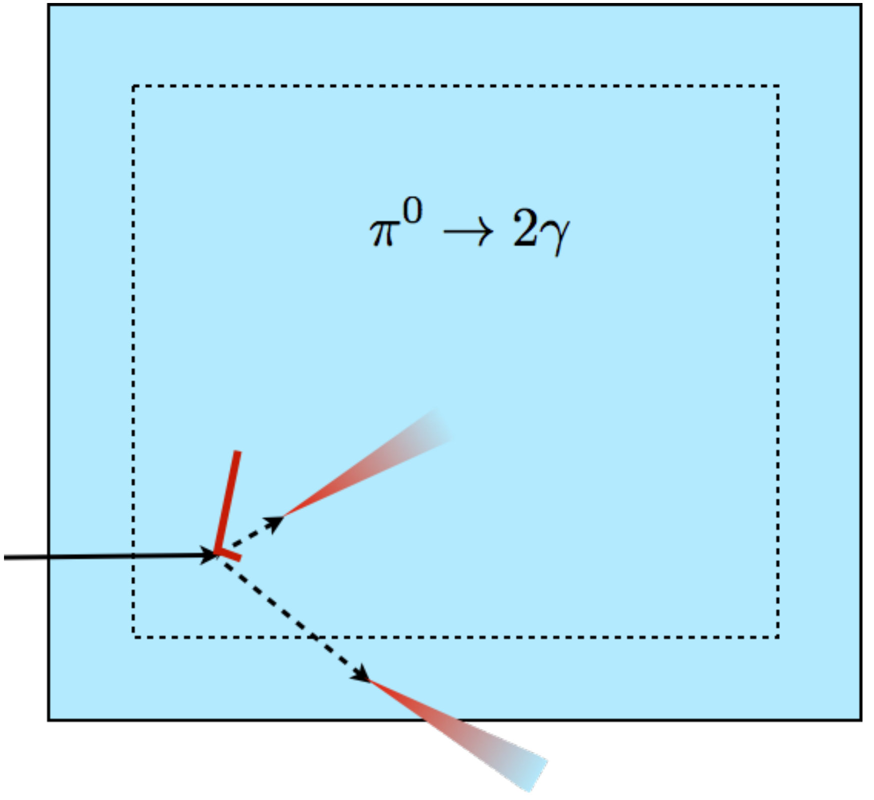
Neutral Current MisID

Neutral current events can produce a photon that can be misidentified as an electron.

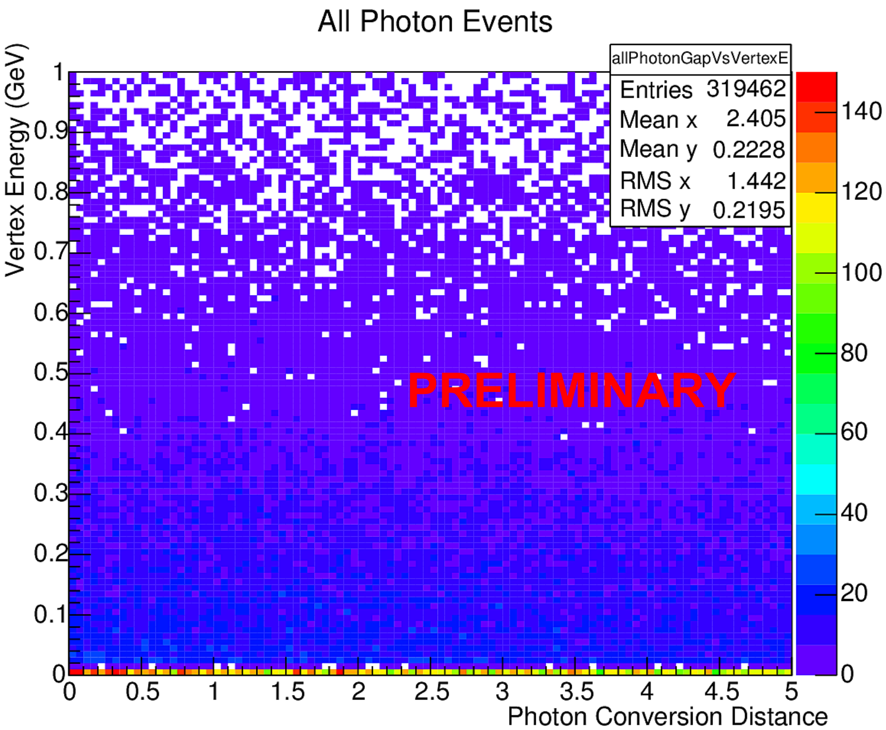
Shower can be rejected if:

→ dEdX positively identifies it as a photon, **OR**

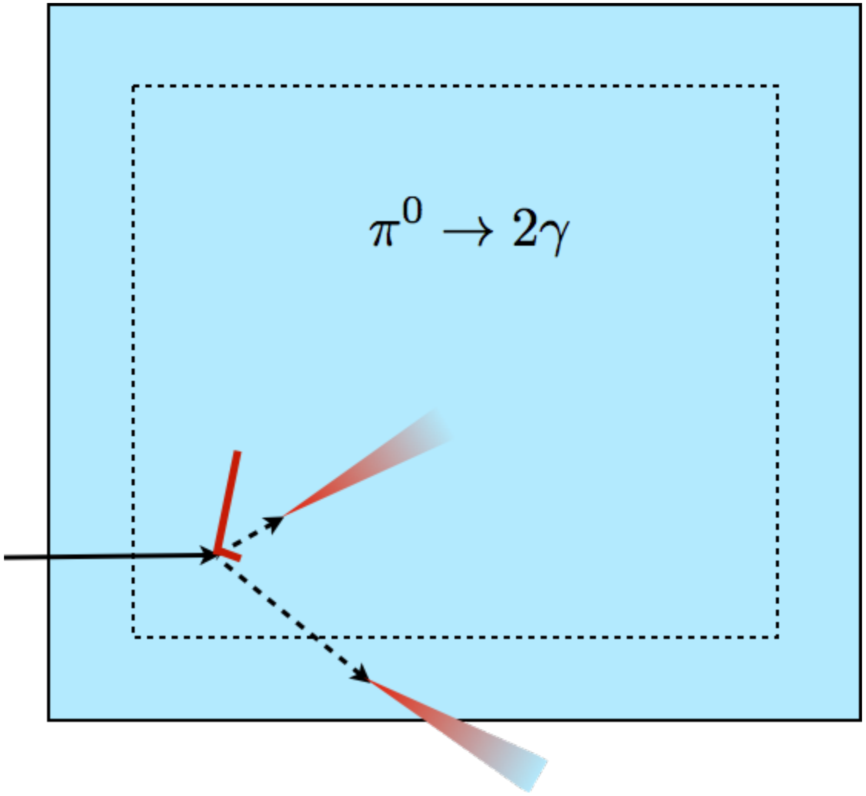
→ There is a visible gap between the photon and an interaction vertex



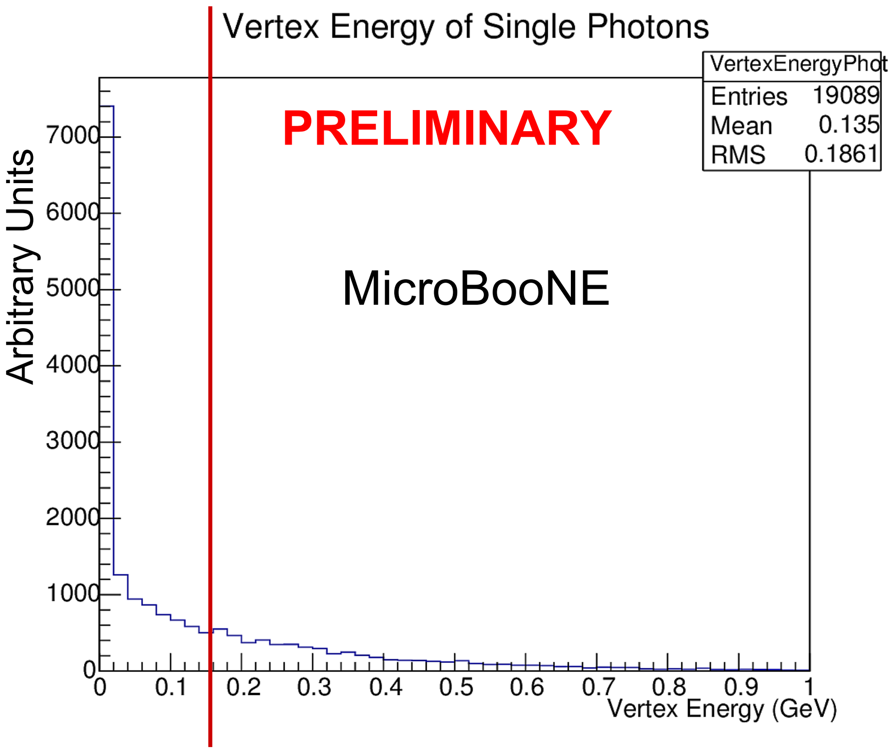
Neutral Current MisID

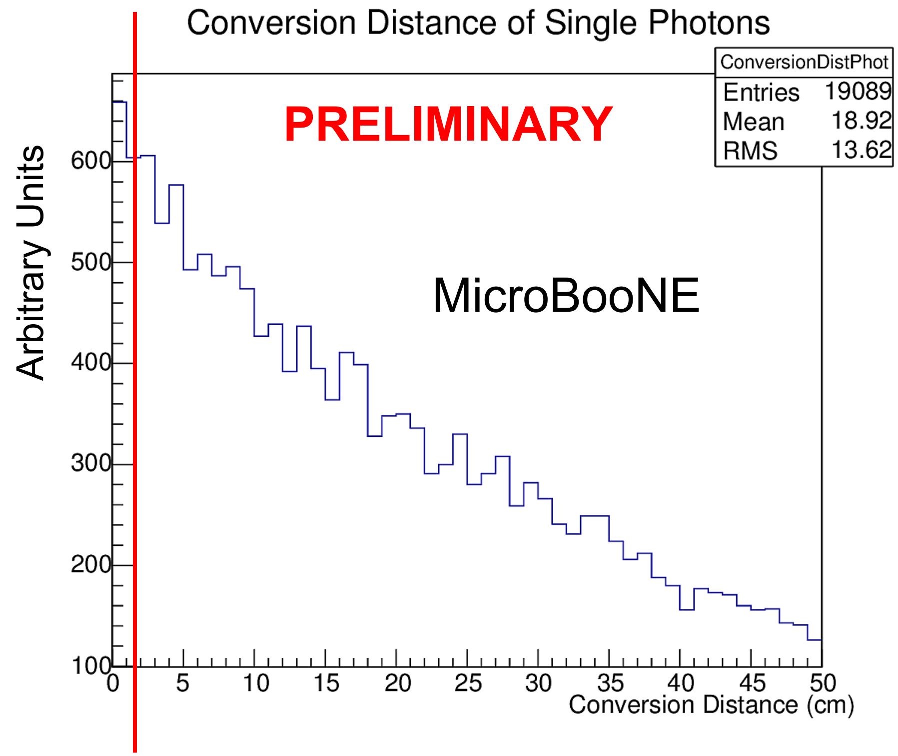


The distribution of vertex energy versus photon conversion distance for all photons in MicroBooNE.



Neutral Current MisID



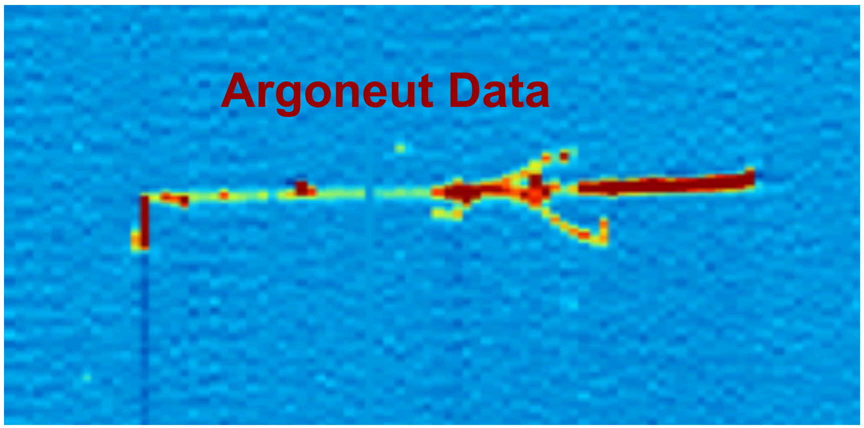


Can reject single photons if the vertex activity is high enough AND the gap between the vertex and the shower is big enough.

Neutral Current MisID

- Any event with multiple photons is rejected.
  - Therefore, all NC MisID have exactly one photon
- If that photon is from an interaction with more than 150 MeV of visible energy at the vertex, AND if travels more than 1.5cm from that vertex (5 wires), it is rejected
- The rest of the single photons are kept at a 6% rate to account for the failure of a dE/dX cut.

Charged Current MisID



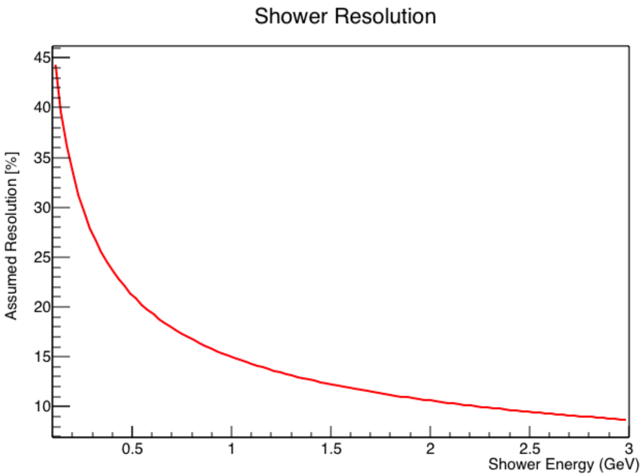
Argoneut event that we found when searching for electrons but is tagged as a muon by MINOS - one possible topology for misID is an exiting muon with showering activity like above.

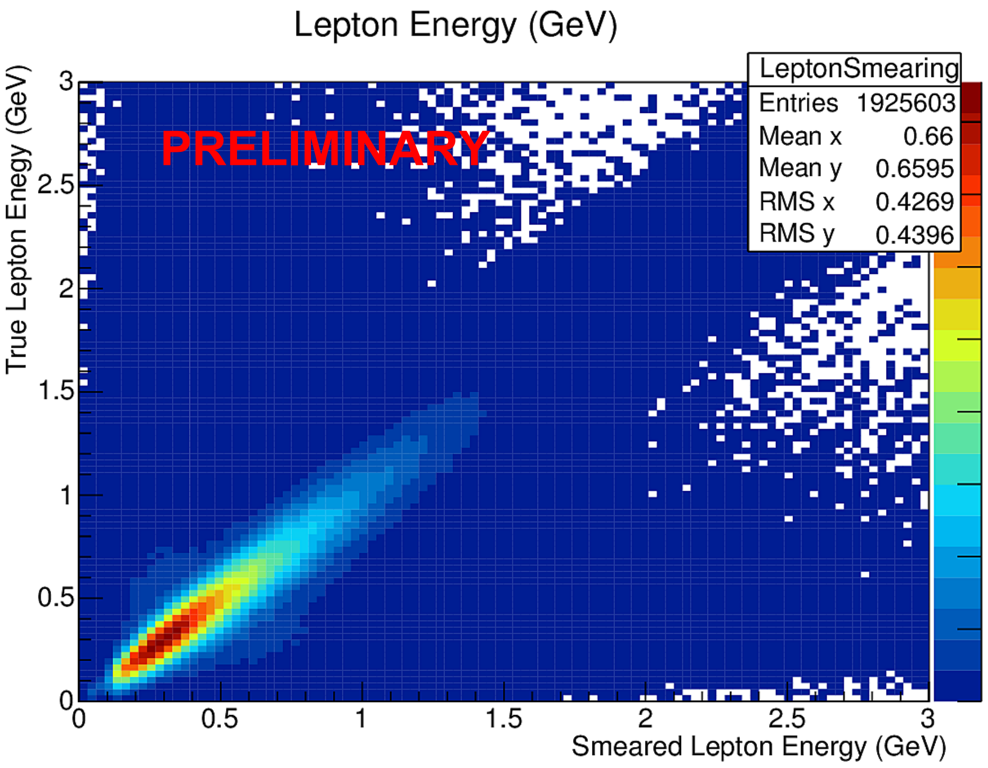
This background is not well determined - there have been many conflicting studies on the size of the mis ID from Charged Current $\nu_{\square}$.

➔ Requires a more careful study, so using **flat 0.1%.**

Shower Energy Reconstruction

Smearing showers with a resolution of 15%/√(E)





Hadronic Energy Reconstruction

All charged hadrons at the neutrino vertex are assumed to be “visible” if they have more than 20 MeV of Kinetic Energy.

Vertex Energy is defined as the energy from a neutrino interaction: Proton KE, but Pion total E and Kaon total E.

All vertex energy has a 5% resolution.

ν_μ Event Candidates

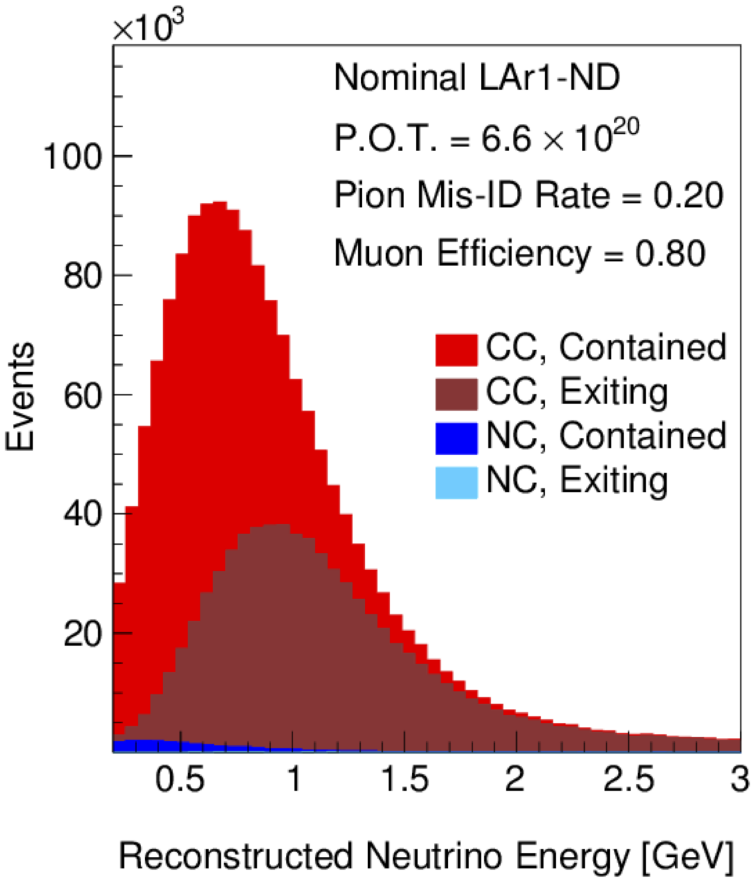
ν_μ events are:

- Charged Current ν_μ interactions that produce a muon
- Neutral Current events with charged pions - how to distinguish from muons?

Because the number of ν_μ CC interactions is so high, this analysis is (for practical purposes) background free

ν_μ Event Candidates

<u>Example Background Study</u>



ν_μ events are accepted at 80% efficiency

NC Events are kept at 20% mis identification rate.

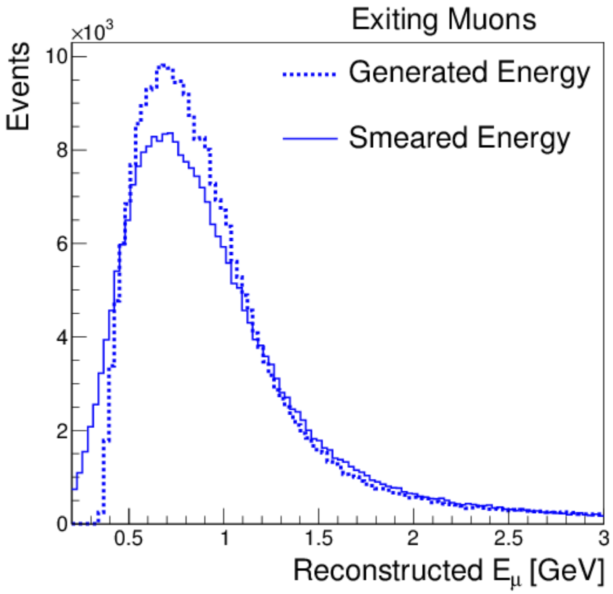
There is a different smearing applied based on containment - more on that very soon.

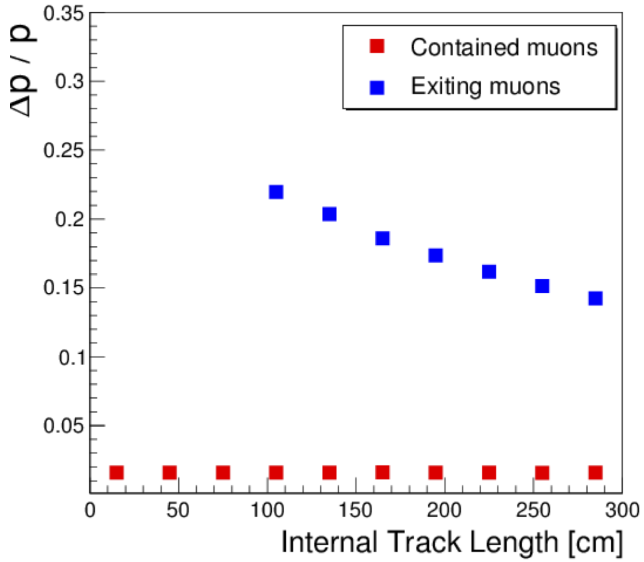
NC Background deemed negligible

Muon Energy Reconstruction

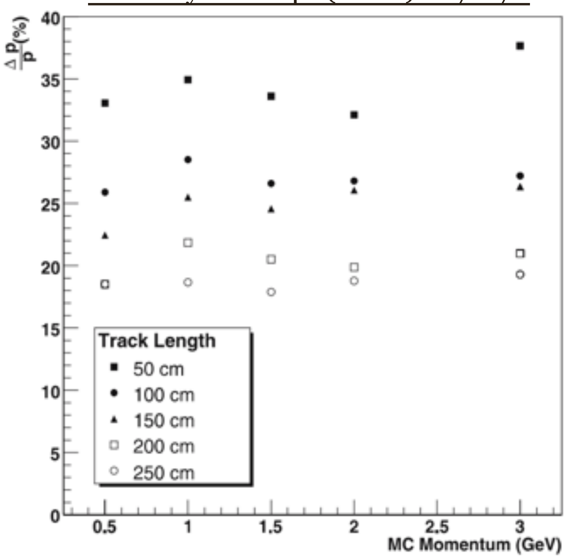
Apply a gaussian energy smearing with the width set to:

- 2%, for contained tracks
- Based upon Multiple Coulomb Scattering measurements performed by ICARUS, for exiting track with length >1m



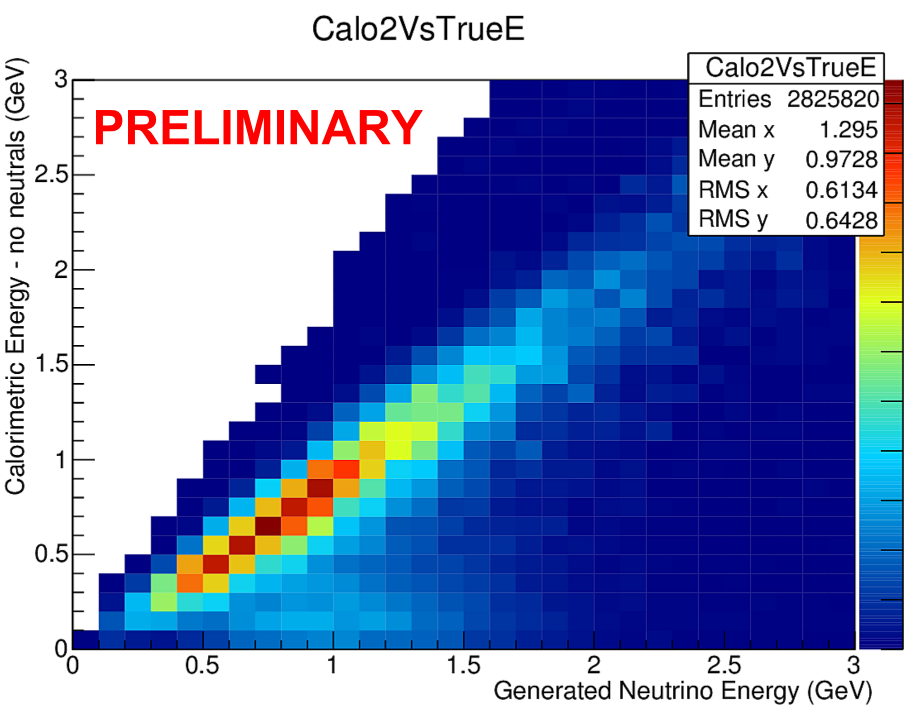


Eur. Phys. J. C 48 (2006) 667-676

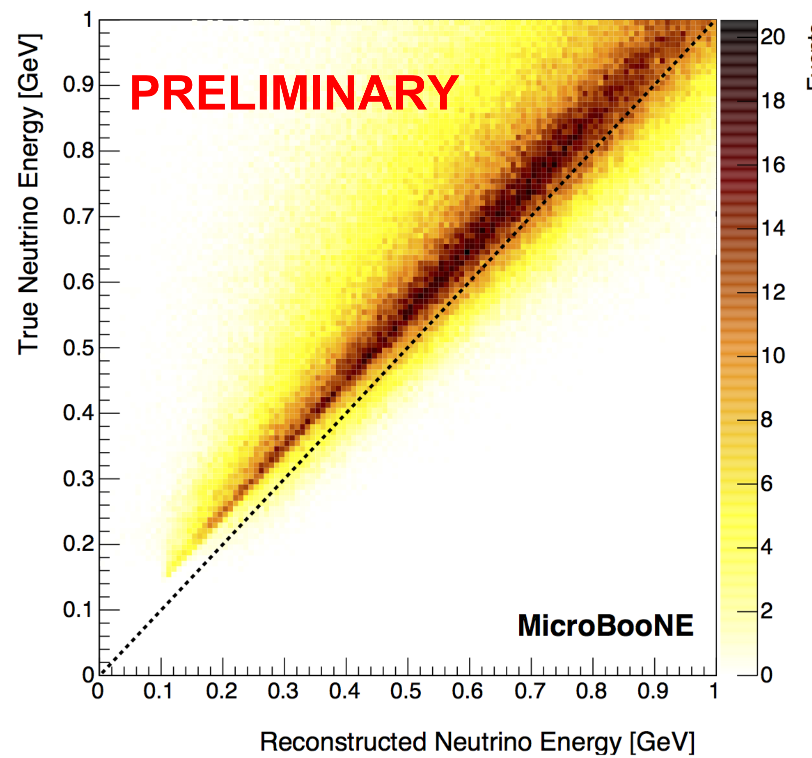


Neutrino Energy Reconstruction

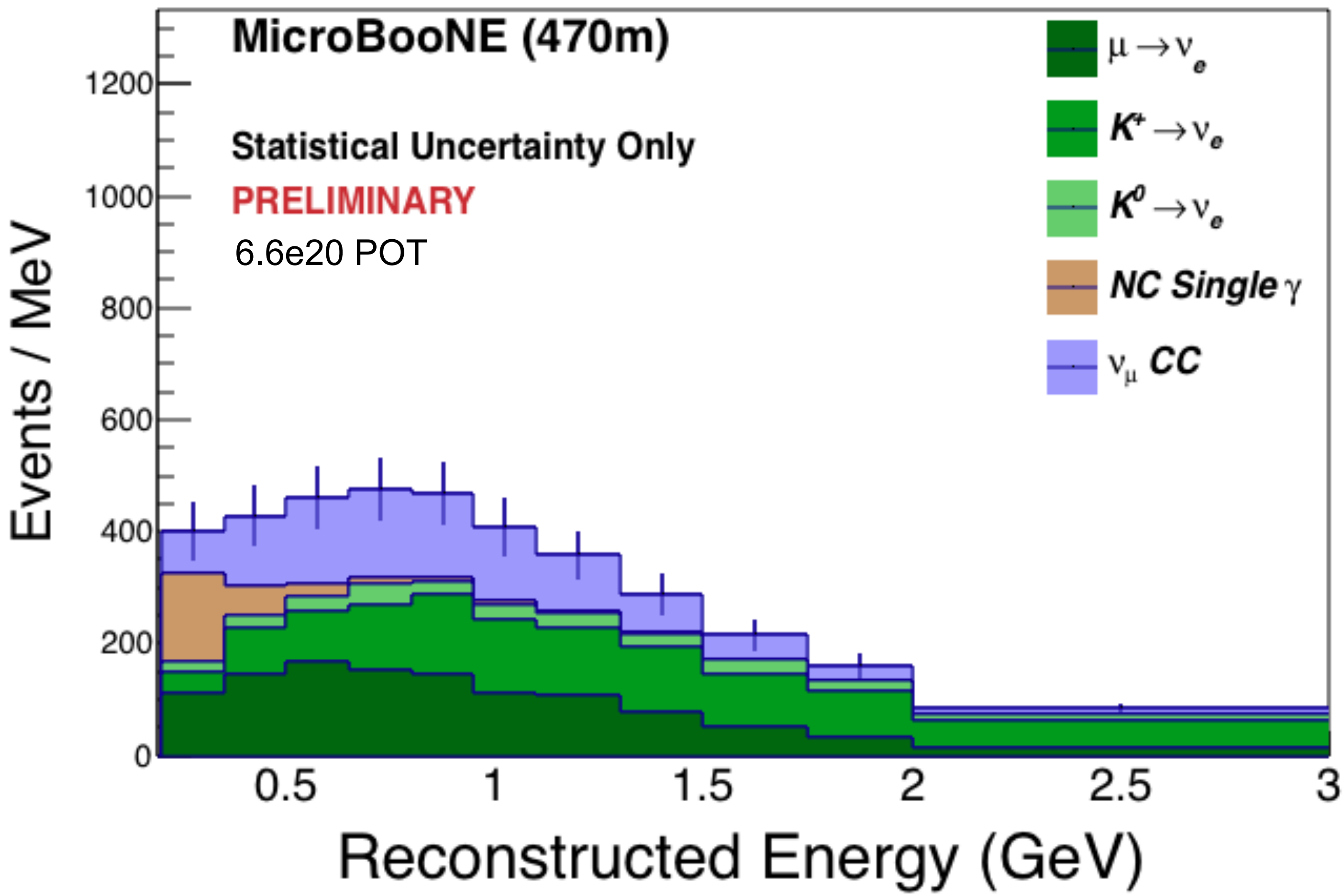
Generated Neutrino Energy Vs. Reconstructed Energy - ν_e



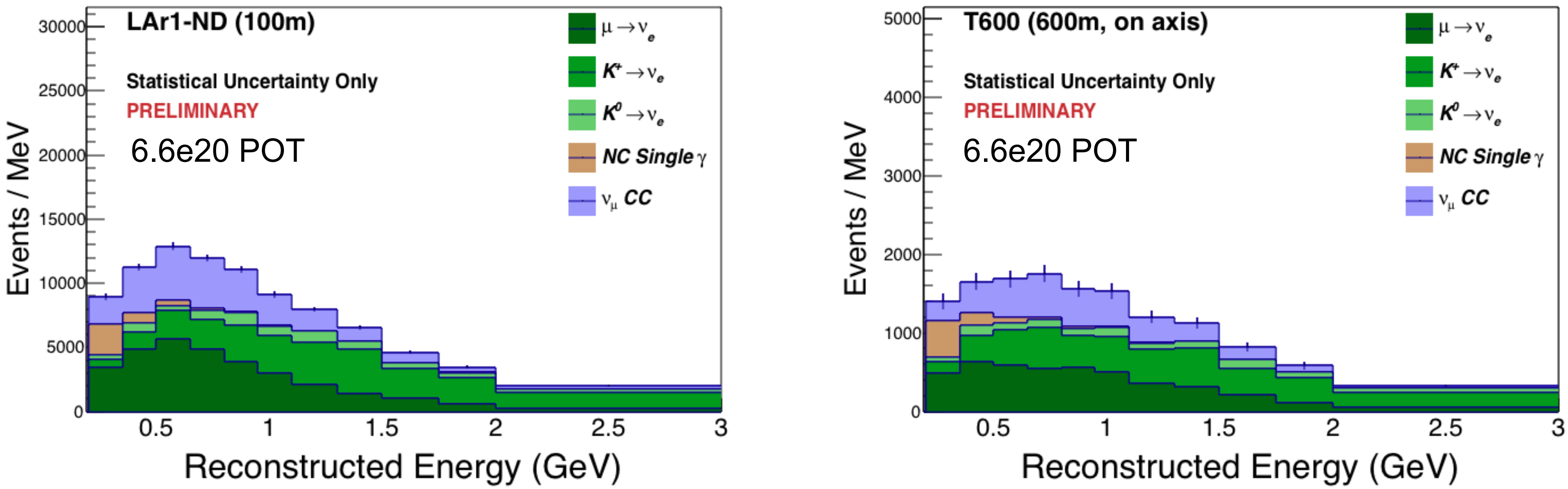
Reconstructed Energy Vs. Generated Neutrino Energy - ν_μ



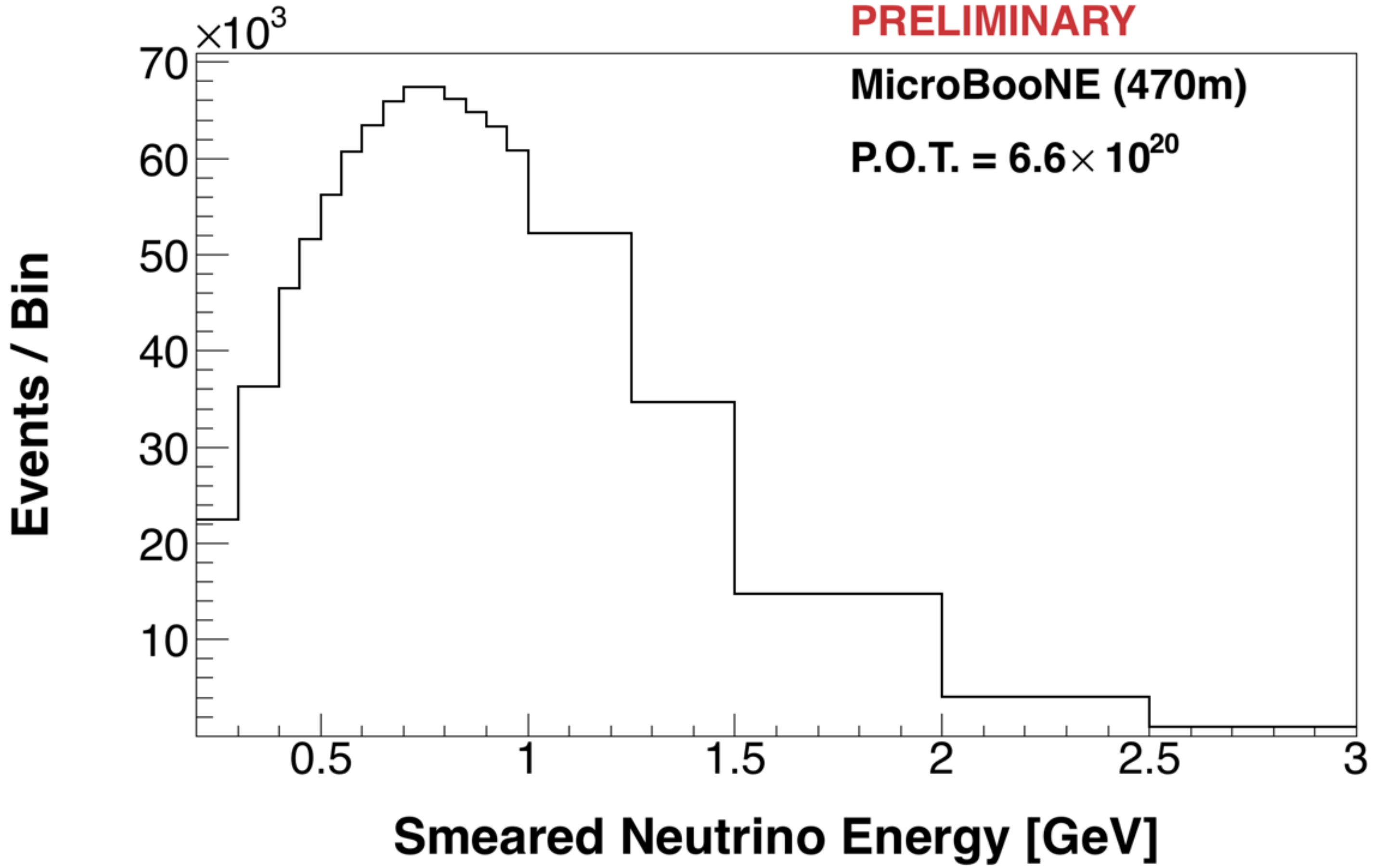
MicroBooNE ν_e



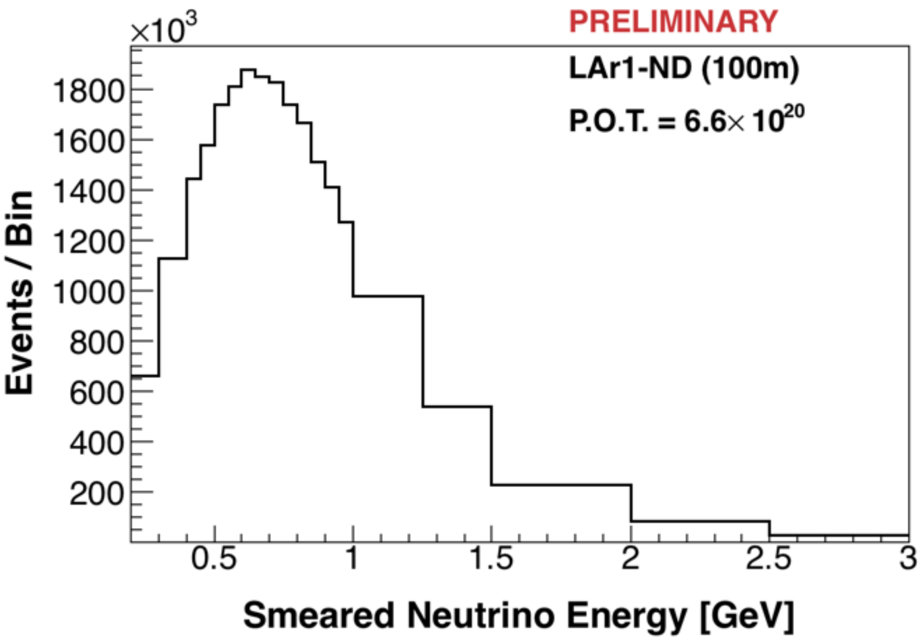
LAr1-ND, T600 ν_e

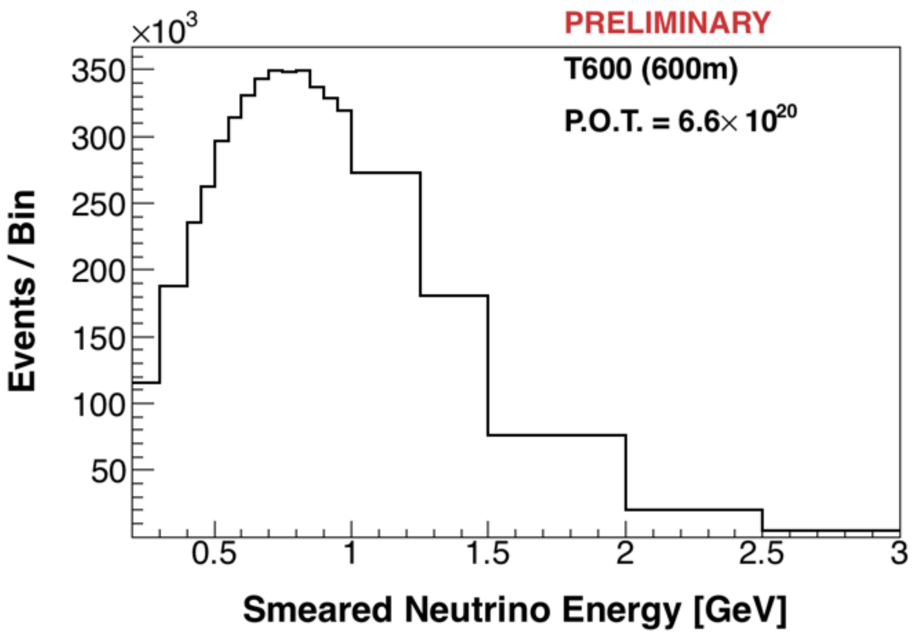


MicroBooNE ν_μ



LAr1-ND, T600 ν_μ

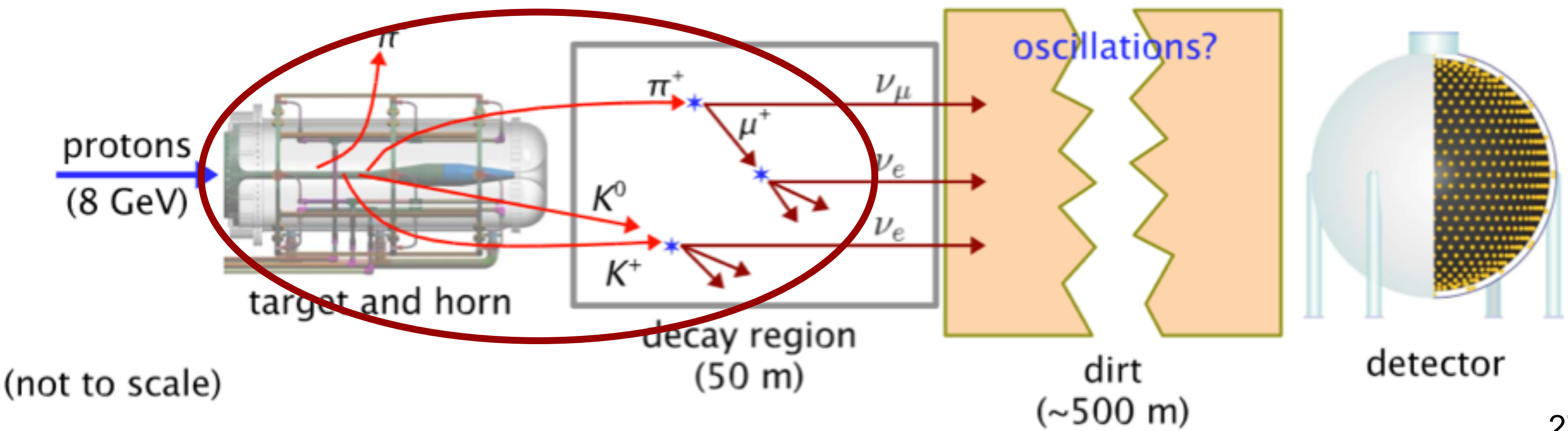




Flux Uncertainties

Beam uncertainties

We focus on understanding the uncertainty in the neutrino flux coming from the hadron production at the target, as well as off target and secondary interactions



Underlying Uncertainties

- π^+ production in primary p+Be collisions at 8 GeV.
- π^- production in primary p+Be collisions at 8 GeV.
- K^+ production in primary p+Be collisions at 8 GeV.
- K^- production in primary p+Be collisions at 8 GeV.
- K_L^0 production in primary p+Be collisions at 8 GeV.
- Primary hadron production from non-target interactions
- Beam focusing uncertainties.

Propagation of Weights

Each weight is carried with the neutrinos that reach the final flux file.

With 1000 “universes”, each neutrino has a weight that corresponds to each “universe”.

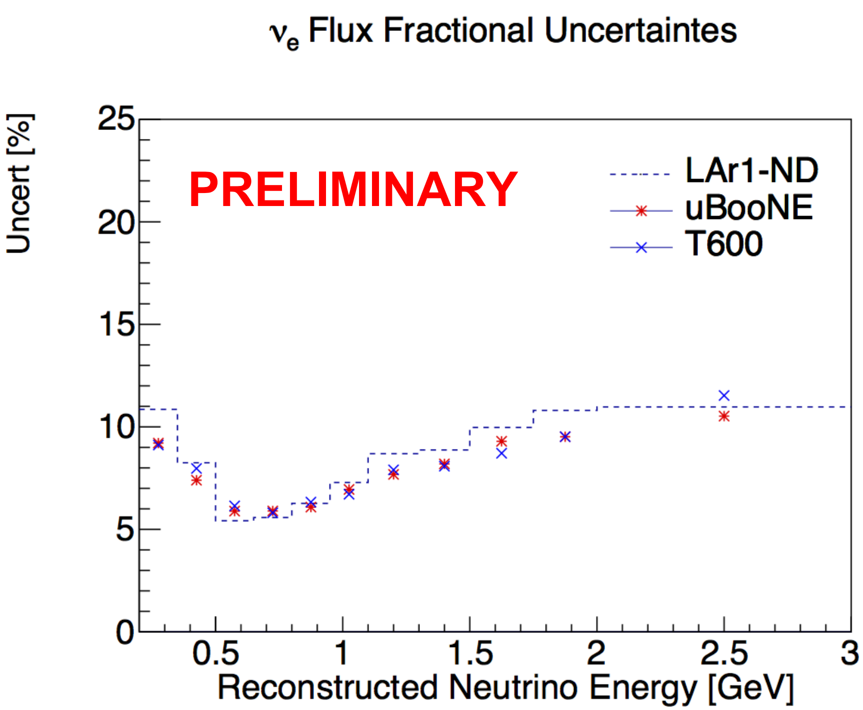
These weights allow us to study correlations.

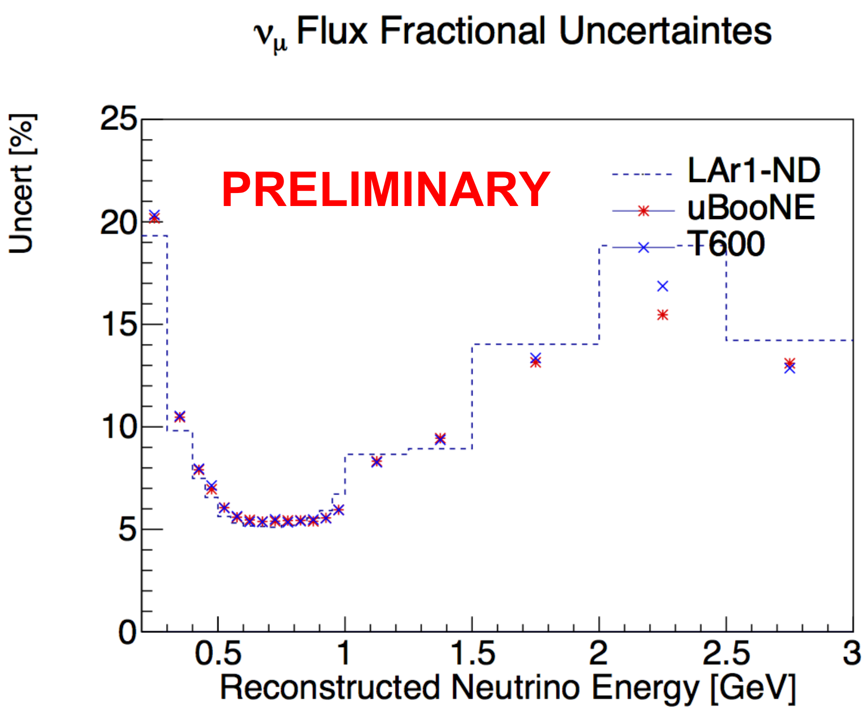
Absolute Flux Uncert.

By building the event rate distribution in each "universe", we get a spread of possible outcomes within the flux uncertainty.

The bin by bin RMS can be used to look at the absolute flux uncertainty on the event rates.

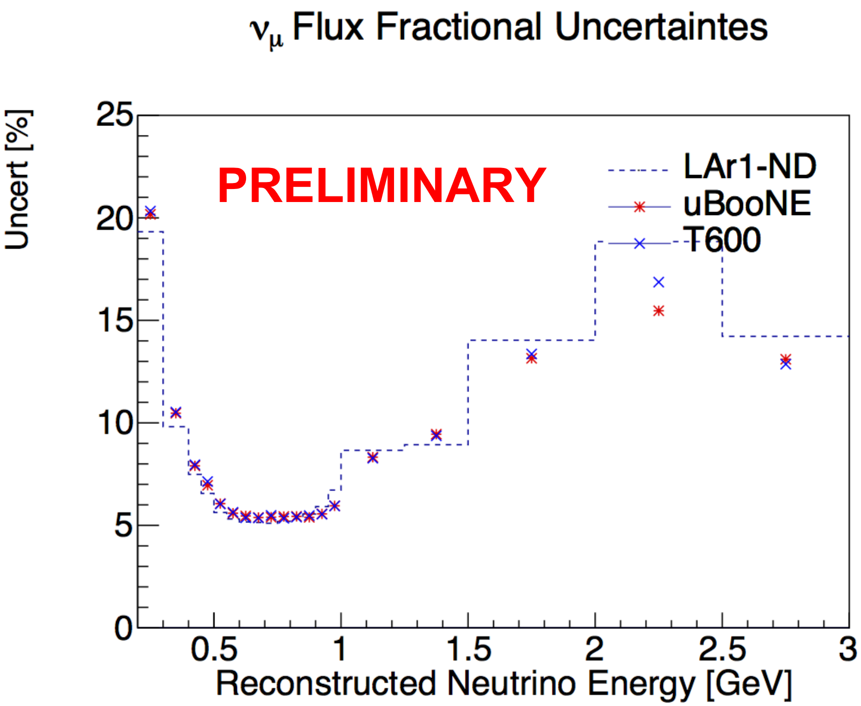
Absolute flux Uncert.





Absolute flux Uncert.

Source of Uncertainty	ν_μ	ν_e
π^+ production	14.7%	9.3%
π^- production	0.0%	0.0%
K^+ production	0.9%	11.5%
K^0 production	0.0%	2.1%
Horn field	2.2%	0.6%
Nucleon cross sections	2.8%	3.3%
Pion cross sections	1.2%	0.8%



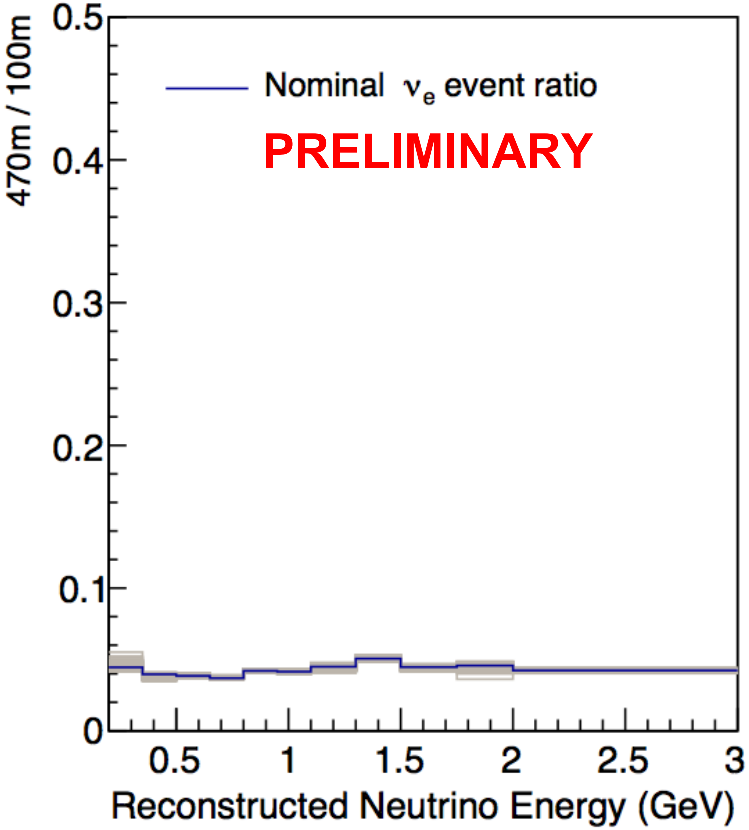
Correlated Uncertainties

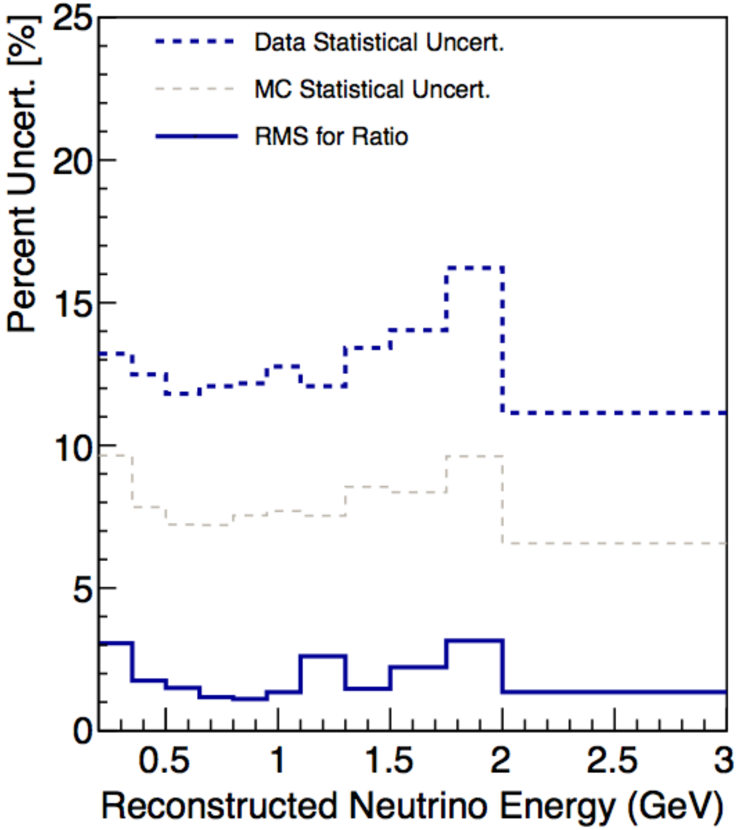
Beam fluctuations should be correlated between detectors!

In particular, if the flux in one “universe” changes at one detector, it should change in a very similar way at another detector.

Therefore, the ratio of far detector to near detector event rates should have much less uncertainty.

Ratio of Far to Near





Cross Section Uncertainties

Underlying Uncertainties

Neutrino Cross sections are one of the biggest uncertainties that affect the normalization of our expected backgrounds.

By varying the underlying physical parameters from which the uncertainties originate, and computing event weights (just like in the flux uncertainties), we can quantify the amount of uncertainty coming from cross sections.

Physical Parameters Varied

PRELIMINARY

Parameter	Description	Nominal %
M_A^{CCQE}	Axial mass for CC quasi-elastic	-15%+25%
M_A^{CCRES}	Axial mass for CC resonance neutrino production	±20%
M_A^{NCRES}	Axial mass for NC resonance neutrino production	±20%
$R_{bkg}^{\nu p,CC1\pi}$	Non-resonance background in $\nu p, CC$ 1π reactions.	±50%
$R_{bkg}^{\nu p,CC2\pi}$	Non-resonance background in $\nu p, CC$ 2π reactions.	±50%
$R_{bkg}^{\nu n,CC1\pi}$	Non-resonance background in $\nu n, CC$ 1π reactions.	±50%
$R_{bkg}^{\nu n,CC2\pi}$	Non-resonance background in $\nu n, CC$ 2π reactions.	±50%
$R_{bkg}^{\nu p,NC1\pi}$	Non-resonance background in $\nu p, NC$ 1π reactions.	±50%
$R_{bkg}^{\nu p,NC2\pi}$	Non-resonance background in $\nu p, NC$ 2π reactions.	±50%
$R_{bkg}^{\nu n,NC1\pi}$	Non-resonance background in $\nu n, NC$ 1π reactions.	±50%
$R_{bkg}^{\nu n,NC2\pi}$	Non-resonance background in $\nu n, NC$ 2π reactions.	±50%
$DIS - NuclMod$	DIS Nuclear Modification	
NC	Neutral Current	

Propagation of Weights

Each neutrino gets 250 weights from a random, fluctuation of all underlying physical parameters (each drawn from a 1 sigma gaussian for that parameter).

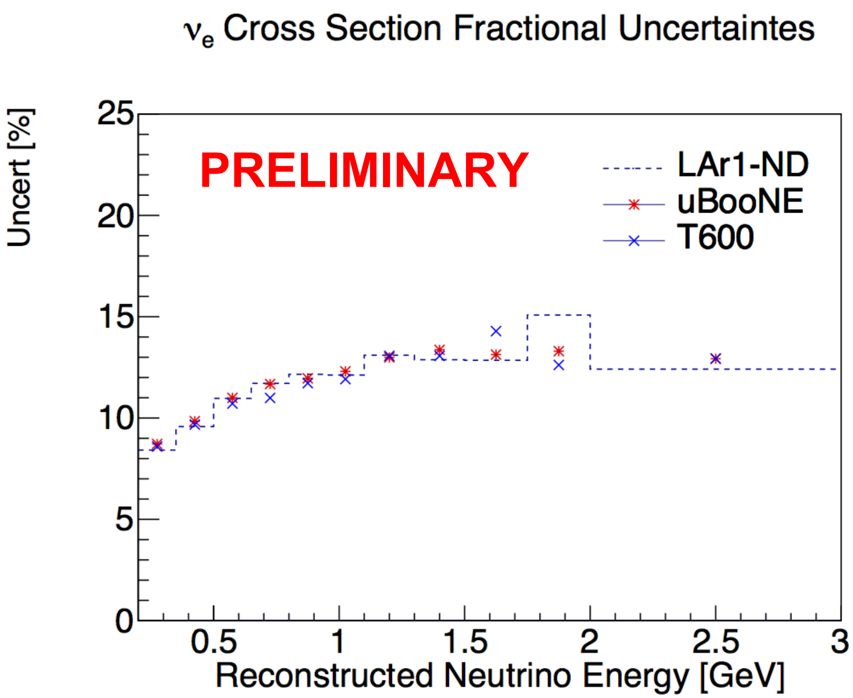
With 250 “universes”, each neutrino has a weight that corresponds to each “universe”.

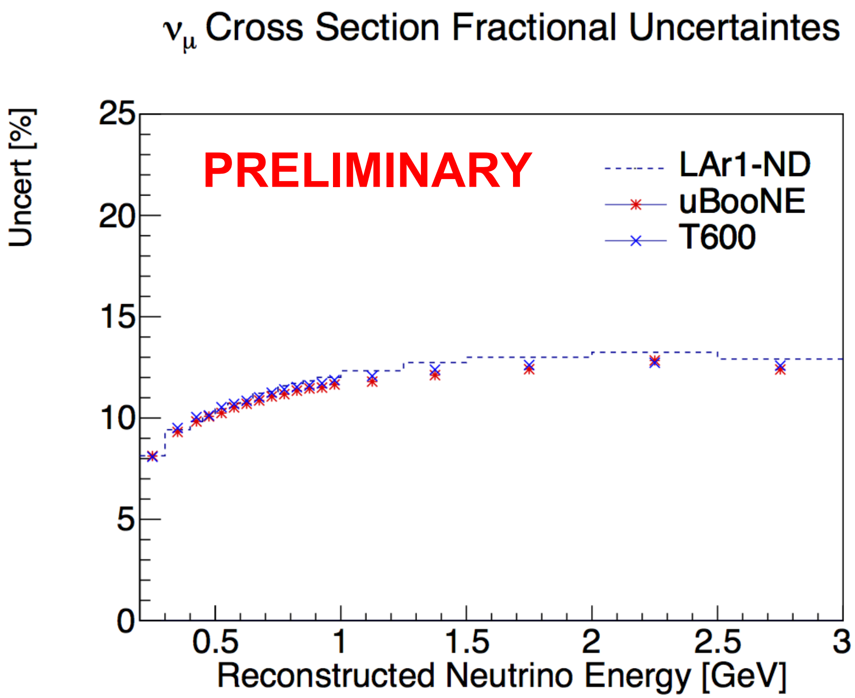
Absolute Cross Section uncerts.

By building the event rate distribution in each "universe", we get a spread of possible outcomes within the ~~flux~~ cross section uncertainty.

The bin by bin RMS can be used to look at the absolute ~~flux~~ cross section uncertainty on the event rates.

Absolute Cross Section uncert





Correlations

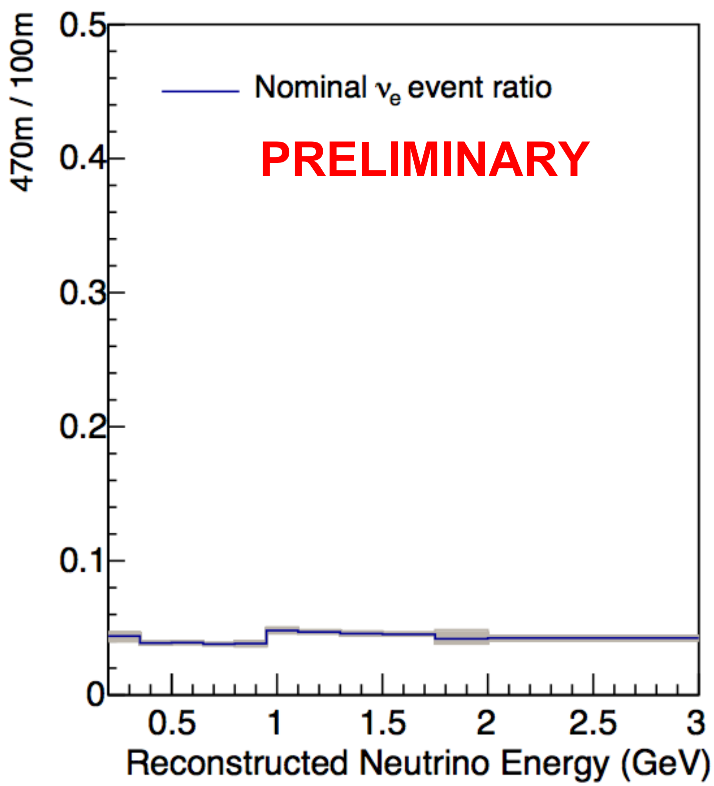
~~Beam~~ Cross Section fluctuations should be correlated between detectors!

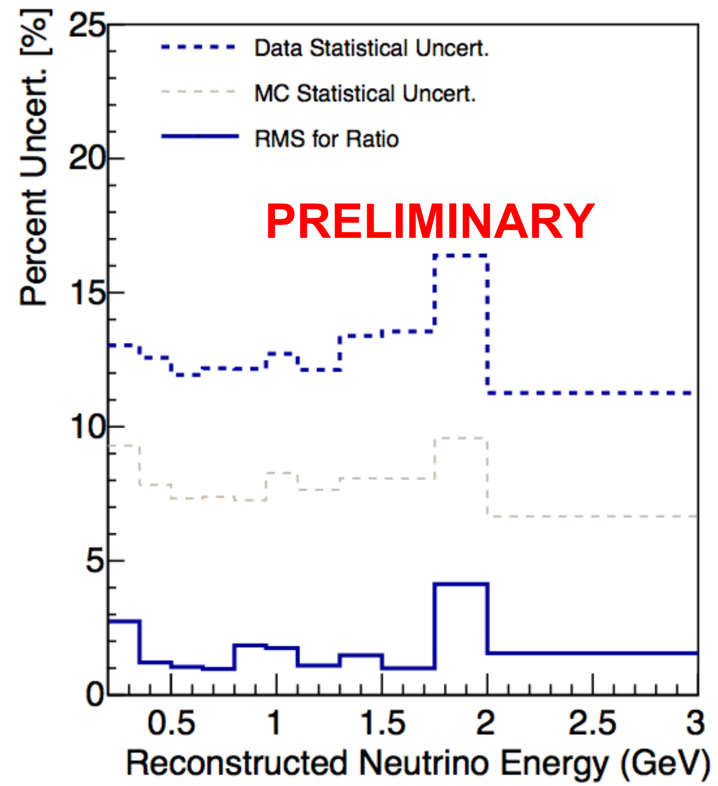
In particular, if the ~~flux~~ cross section in one “universe” changes at one detector, it should change in a very similar way at another detector.

Therefore, the ratio of far detector to near detector event rates should have much less uncertainty.

Ratio plots

ν_e Nominal Ratio (dark) and ratio in each universe (gray)





Interlude: Analysis Methods

What is the proper way to handle the bin to bin and detector to detector correlations in calculating a sensitivity to a signal? **Use a covariance matrix.**

Start by defining a nominal event rate vector as the concatenation of the event rates at individual detectors:

$$N_{CV} = (n^1_{ND},\ n^2_{ND},\ ...,\ n^k_{ND},\ n^1_{uB}, ...)$$

Event Rate in Each "Universe"

Define the same vector in each "universe" of a systematic like flux, or cross section:

$$N_{flux,1} = (n^1_{ND,flux,1},\ n^2_{ND,flux,1},\ \ldots,\ n^k_{ND,flux,1},\ n^1_{uB,flux,1}, \ldots)$$

$$N_{flux,\alpha} = (n^1_{ND,flux,\alpha},\ n^2_{ND,flux,\alpha},\ \ldots,\ n^k_{ND,flux,\alpha},\ n^1_{uB,flux,\alpha}, \ldots)$$

$$N_{flux,\mathcal{N}} = (n^1_{ND,flux,\mathcal{N}},\ n^2_{ND,flux,\mathcal{N}},\ \ldots,\ n^k_{ND,flux,\mathcal{N}},\ n^1_{uB,flux,\mathcal{N}}, \ldots)$$

Covariance Matrix

With each event rate vector, we make a covariance matrix:

$$E_{i,j}^{flux} \equiv \frac{1}{\mathcal{N}} \sum_{m=1}^{\mathcal{N}} [N_{CV}^{i} - N_{flux,m}^{i}] \times [N_{CV}^{j} - N_{flux,m}^{j}]$$

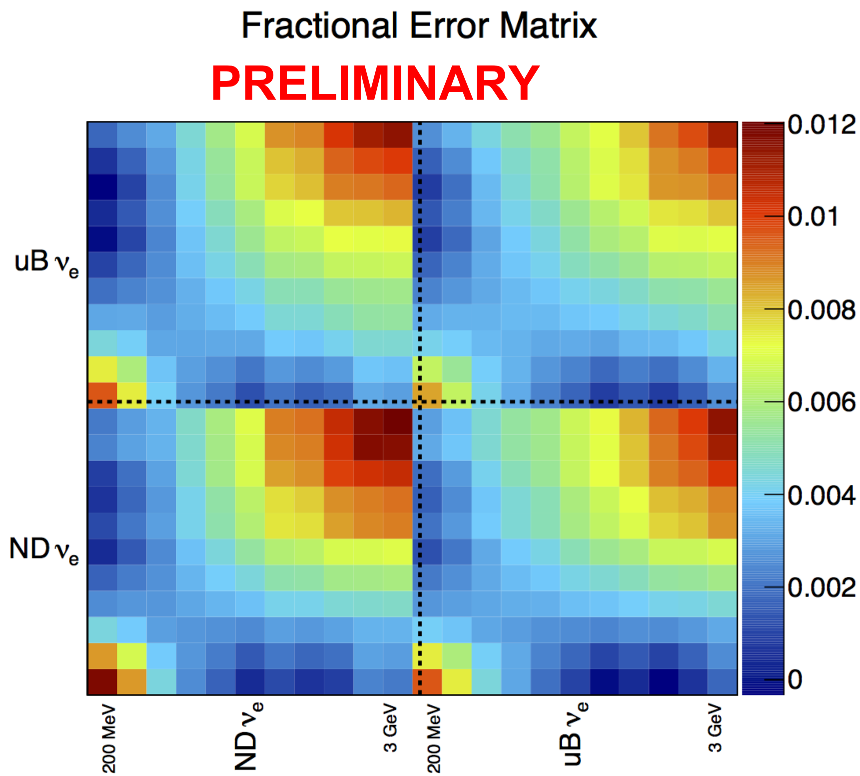
This matrix is the essential tool for doing a multidetector analysis.

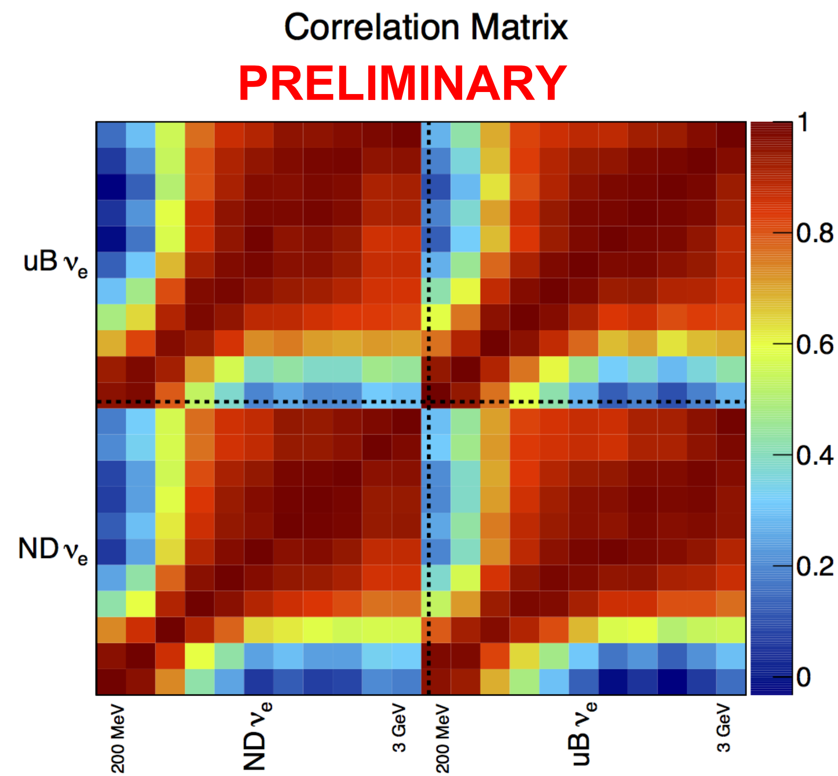
Correlation Matrix Fractional Cov. Matrix

The covariance matrix is easier to digest when transformed into a fractional matrix or a correlation matrix:

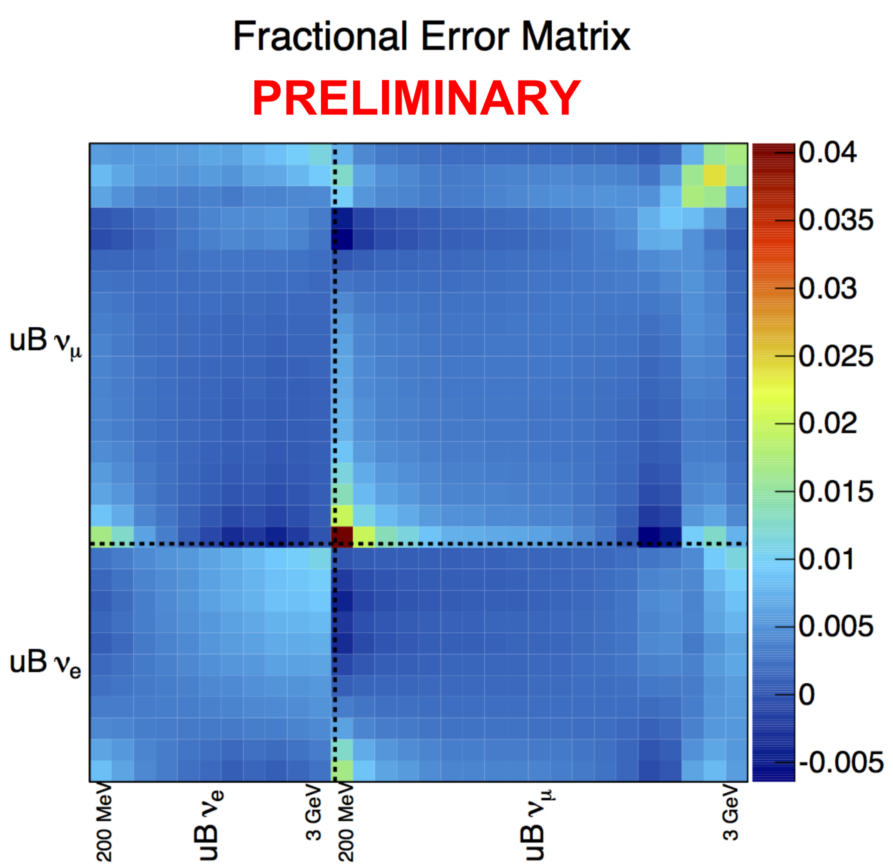
$$F_{i,j}^{sys} \equiv \frac{E_{i,j}^{sys}}{(N_{CV}^{i}\ N_{CV}^{j})} \qquad C_{i,j}^{sys} \equiv \frac{E_{i,j}^{sys}}{\sqrt{E_{i,i}^{sys}}\ \sqrt{E_{j,j}^{sys}}}$$

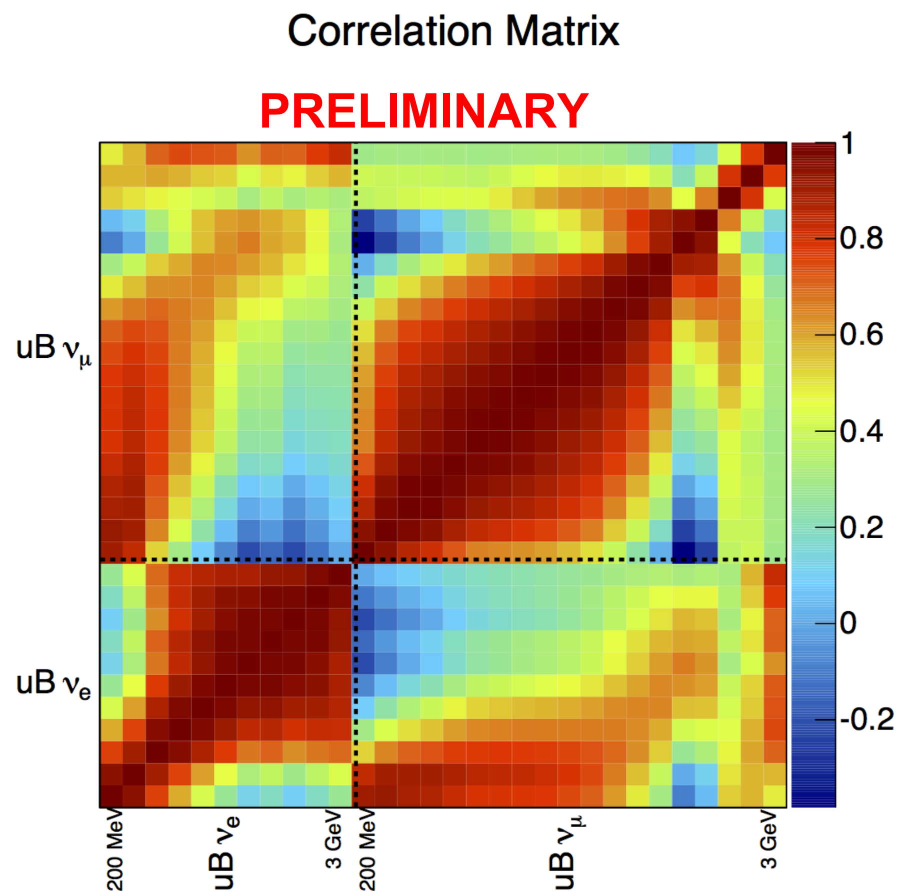
Flux Matrices - ν_e



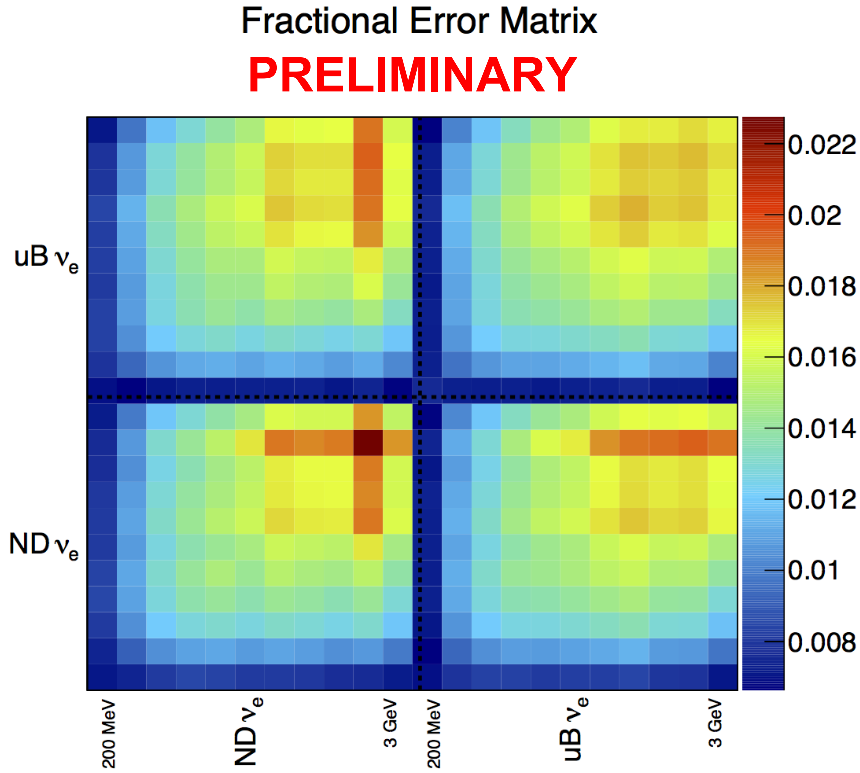


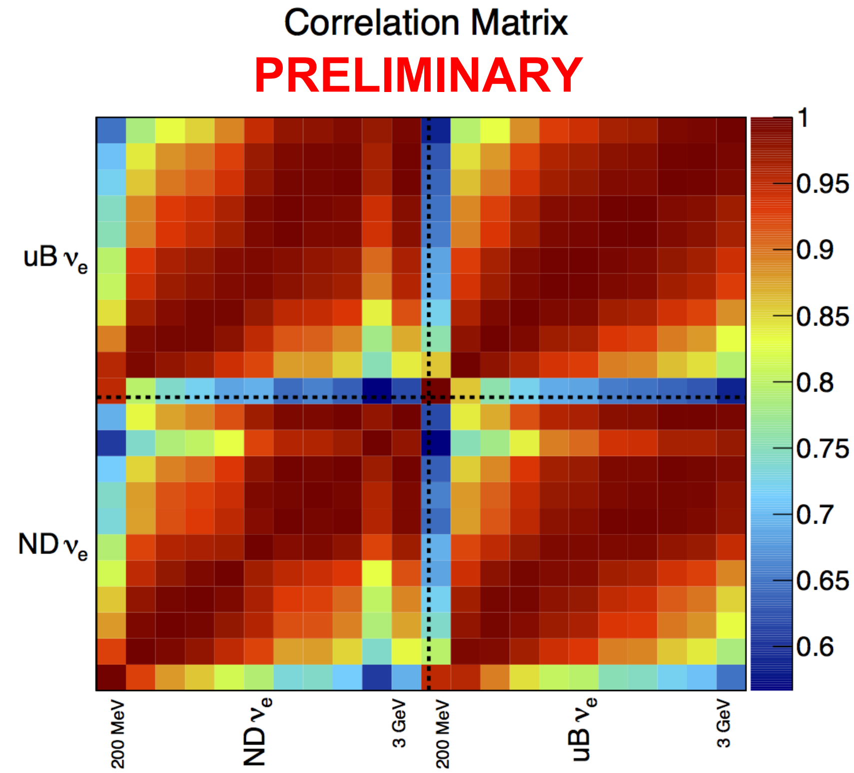
Flux Matrices - ν_e and ν_μ





Cross Section Matrices - ν_e

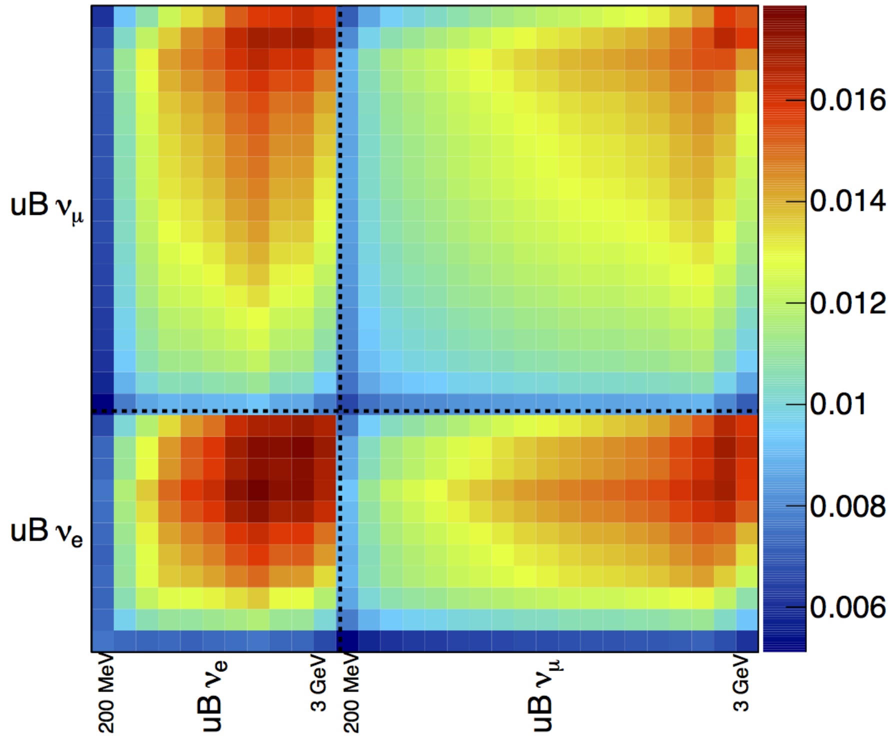




Cross Section - ν_e and ν_μ

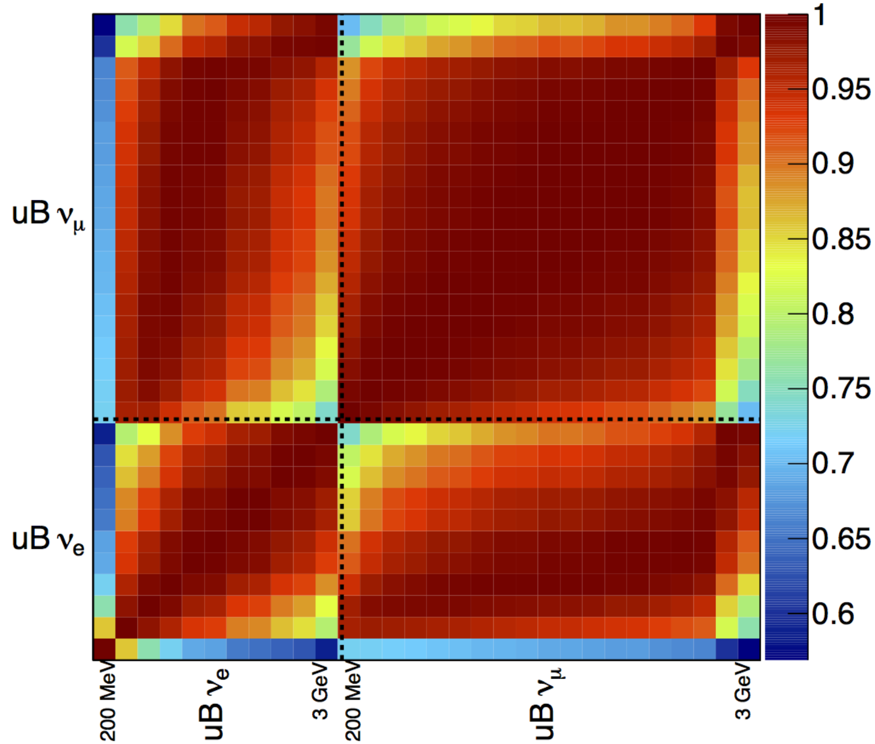
Fractional Error Matrix

PRELIMINARY



Correlation Matrix

PRELIMINARY



Sensitivity Calculations

Simulating a Signal

To quantify the reach of the Short Baseline Program, we need to work in the context of some oscillations framework, and so we choose the 3+1 model.

$$P(\nu_\mu \to \nu_s) = \sin^2 2\theta \times \sin\left(1.267 \frac{\text{GeV}}{\text{eV}^2\ \text{km}} \frac{L}{E} \Delta m^2\right)$$

We can vary the amplitude and mass splitting to simulate different oscillation scenarios within the 3+1 framework

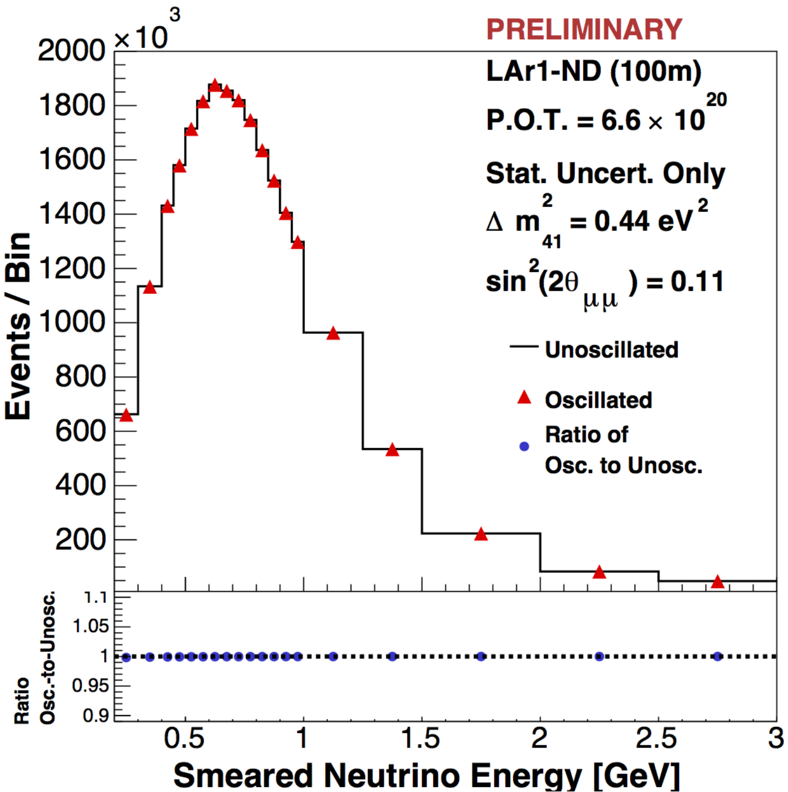
ν_μ Oscillation Signal

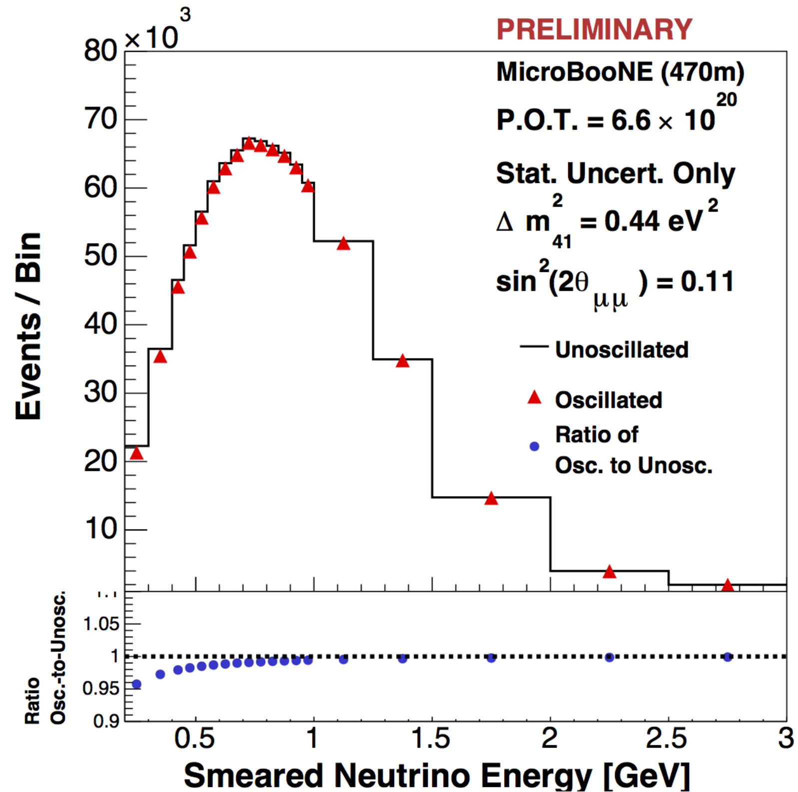
The oscillation of the ν_μ spectrum is assumed to be the disappearance of muon neutrinos into sterile neutrinos.

We sample a series of possible combinations of $\sin^2 2\theta$ and Δm^2 drawn from reasonable ranges based on existing limits, like MiniBooNE + SciBooNE muon disappearance.

ν_μ Oscillation Signal

Signal is same mass splitting as Global Best Fit, but different amplitude.





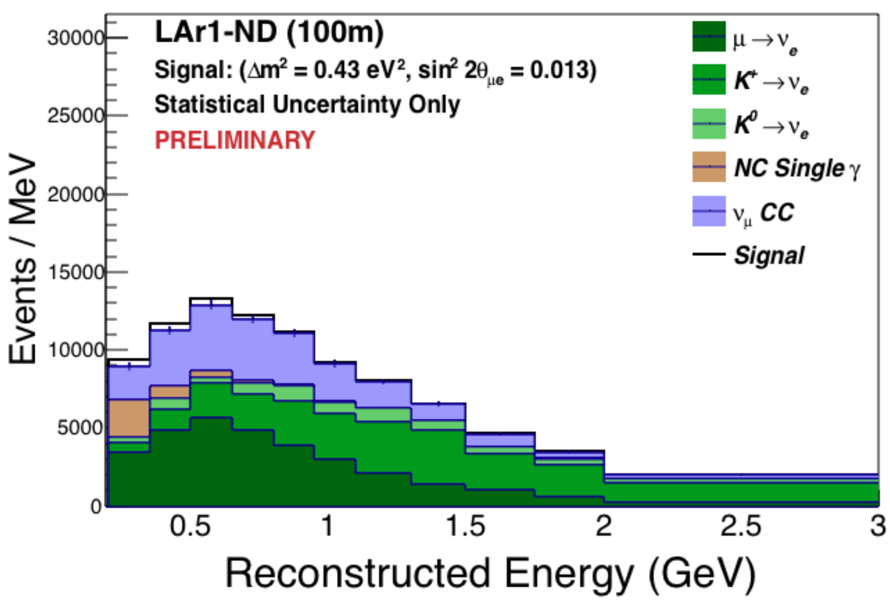
ν_e Oscillation Signal

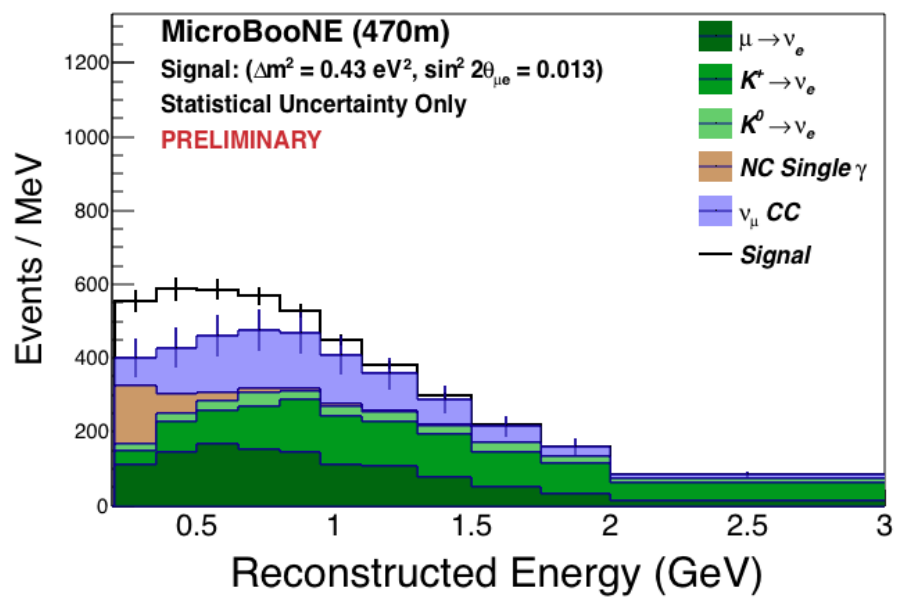
The oscillation of the ν_e spectrum is assumed to be the disappearance of muon neutrinos into electron neutrinos through an intermediate sterile neutrino.

We show a sensitivity over the whole LSND allowed region as a comparison to existing anomalies.

ν_e Oscillation Spectrum

Signal Point is Global Best Fit from Kopp et al. (arxiv 1303.3011)





Calculating a Sensitivity

The addition of oscillation changes the expected event rates:

$$\mathcal{N} \equiv \mathcal{N}(\Delta m^2, \sin^2 2\theta)$$

We can use the difference between "oscillated" spectrum and predicted background to calculated a χ^2 for each point of (Δm^2, $\sin^2 2\theta$)

$$\chi^2 \equiv \sum_{i,j} [\mathcal{N}^i_{null} - \mathcal{N}^i(\Delta m^2, \sin^2 2\theta)] \times (E^{total}_{i,j})^{-1} \times [\mathcal{N}^j_{null} - \mathcal{N}^j(\Delta m^2, \sin^2 2\theta)]$$

Total Covariance Matrix

Flux - Already covered

Xsec - Already covered

Dirt - Joseph's Talk

Cosmic - *In progress*

Detector - *In progress*

Statistical - Diagonal only, √(n)

$$E^{total} = E^{flux} + E^{xsec} + E^{dirt} + E^{cosmic} + E^{det} + E^{stat}$$

Full Sensitivities

The Short Baseline document will include expected sensitivities, using the total covariance matrix, in a shape + rate analysis (which is what was described above).

A realistic set of exposures will be used (ND = 3 years, uB = 6 years, T600 = 3 years) based upon the proposed schedule.

The LAr1-ND Conceptual Design Report Plans to include several physics items that are specifically enabled by the presence of the near detector, some of which involve MicroBooNE:

- Scaling of the Low Energy Excess as seen by LAr1-ND
- Muon Neutrino Appearance “First Look” (200 Days)

Slide 62: Death by Presentation

This was a seriously long talk.

At the next meeting, we will present only the plots for approval since we have already presented all of our assumptions and analysis methods.